EXTRAGALACTIC ABUNDANCES OF HYDROGEN, DEUTERIUM AND HELIUM

New Steps, Missteps and Next Steps

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Abstract. Estimates of the deuterium abundance in quasar absorbers are reviewed, including a brief account of incorrect claims published by the author and a brief review of the problem of hydrogen contamination. It is concluded that the primordial abundance may be universal with a value $(D/H)_P \approx 10^{-4}$, within about a factor of two, corresponding to $\Omega_B h_{0.7}^2 \approx 0.02$ or $\eta_{10} \approx 2.7$ in the Standard Big Bang. This agrees with current limits on primordial helium, $Y_P \leq 0.243$, which are shown to be surprisingly insensitive to models of stellar enrichment. It also agrees with a tabulated sum of the total density of baryons in observed components. Much lower primordial deuterium ($\approx 2 \times 10^{-5}$) is also possible but disagrees with currently estimated helium abundances; the larger baryon density in this case fits better with current models of the Lyman-α forest but requires the bulk of the baryons to be in some currently uncounted form.

1. Introduction

Material in the Earth and other planets, the solar neighborhood, and indeed our entire Galaxy has experienced significant chemical evolution that has modified the traces of light elements from the Big Bang. We are now beginning to sample abundances in more distant environments with a variety of different chemical histories. Some are nearly pristine and serve as fossil beds preserving the original chemistry, particularly those at at high redshift before much of the primordial gas first formed into galaxies and stars. In addition to insights about chemical evolution under different circumstances the new measurements give us unique information about the history of fine-grained structure over an enormous spacetime volume; for example they test the idea that primordial chemistry is the same everywhere and that the primordial gas was precisely uniform on small scales. New techniques also now allow us to tabulate a more reliable direct estimate of the mean baryon density of the Universe in various forms, allowing a further test of Standard Big Bang Nucleosynthesis for which mean total baryon density is the principal parameter.

The theory and its concordance have been extensively reviewed in the literature from many points of view (e.g. Walker *et al.* 1991, Smith *et al.* 1993, Copi *et al.* 1995, Sarkar 1996, Fields *et al.* 1996,, Hogan 1997, Schramm 1998), and many of the topics covered here are reviewed in more detail

elsewhere in this volume. This review explores a selection of interesting contradictions among new extragalactic datasets but also highlights the general concordance with the Standard Big Bang Model.

2. The Cosmic Deuterium Abundance

The measurement of deuterium abundances by analyzing Lyman series absorption lines in stellar spectra from foreground diffuse gas (Rogerson and York 1973) has yielded a reliable abundance for the Galactic interstellar medium, accurate to about $\pm 50\%$. Thanks to new technology the same technique applied to quasar spectra now yields the abundance of much more distant gas (see Tytler 1998, Vidal-Madjar 1998). High resolution, high signal-to-noise spectra allow the study of resolved absorption features of low optical depth which accurately count atomic column densities and thus in principle give reliable abundances. The subject is still very young however; effects of finite resolution and saturation still contribute a subtle source of error (see Levshakov et al. 1998), and the systematic errors are not yet well calibrated since the physical model of the absorbing material is not mature. (It is certainly not, as assumed in the spectral fits, in discrete isothermal slabs). At the moment there is an apparent polarization between “high” and “low” values which seems likely to disappear with time.

2.1. Evidence for a High Abundance

An early Keck spectrum of QSO 0014+813 allowed the first estimate of an extragalactic deuterium abundance, yielding a remarkably high value $D/H \approx 2 \times 10^{-4}$ (Songaila *et al.* 1994). Multiple lines of the Lyman series gave a good agreement of hydrogen and deuterium redshift, and a reliable estimate of both column densities, so the most significant uncertainty in this measurement was the amount of contamination of the deuterium absorption feature by interloping hydrogen.

Subsequent analysis of this same data (Rugers and Hogan 1996a) showed that at full resolution the Lyman-α feature of deuterium was split into two components, each of which was too narrow for hydrogen. The authors used this fact to argue that the hydrogen contamination did not dominate the deuterium feature and therefore that the high abundance could be trusted. The split of the feature was traced back to an electron excess in the raw echellogram data so was not a reduction artifact.

However, in a classic illustration of systematic error it now appears that the feature was not a real spectral feature of the quasar. Subsequent spectra by both the Hawaii group and by Tytler *et al.* (1997), which have better signal-to-noise than the original spectrum, do not confirm it. Apparently

the ≈ 60 electrons contributing to the earlier signal, whatever their origin, were neither simply noise nor photoelectrons from the quasar light. (Similar problems also appear to plague another candidate feature in the same spectrum, proposed by Rugers and Hogan 1996b). The deuterium feature in the real spectrum is instead smooth and is well fit by a single thermally broadened component, so the linewidth is consistent with significant hydrogen contamination. On the other hand the width is the same as the associated hydrogen (24 km/sec) and is therefore also consistent with being caused by deuterium if the broadening is mostly turbulent.

Indeed, the better data allow the redshift of the deuterium and hydrogen features to be compared more precisely and they differ by 10 km/sec, indicating that there is some hydrogen contaminating the deuterium (Tytler *et al.* 1997). However the total column density of contaminating hydrogen required to move the centroid is small, so the known presence of some contamination does not imply that the best estimate of the abundance changes appreciably from that originally given by Songaila *et al.*

Because of the good constraints on both hydrogen and deuterium column densities, and in spite of confusing claims made by this author, the new data on the Q0014+813 absorber still displays good evidence of a high primordial abundance, about as convincing as the original claim by Songaila *et al.* (1994). In another quasar (BR 1202-0725) a "detection or upper limit" at $D/H = 1.5 \times 10^{-4}$ was found by Wampler *et al.* (1996). A high abundance (2×10^{-4}) may also be detected in Q0402-388, although it is required only if OI/HI is assumed to be constant in the fitted components (Carswell *et al.* 1996). The same high abundance (2×10^{-4}) was also found by Webb *et al.* (1997) in Q1718+4807, although this is also not yet conclusive; the present analysis relies on a SiIII line to fix the redshift of the hydrogen, the D column is based only on a Lyman-α fit and the H column on a low resolution spectrum of the Lyman limit. The agreement between these estimates is at least suggestive of a high universal abundance, although none of the evidence is yet conclusive.

2.2. Evidence for a Low Abundance

Burles and Tytler (1996) and Tytler *et al.* (1996) have presented evidence for a low D/H in two quasar absorbers. Of these the stronger case at present is in Q1937-1009 since high quality data are available up to the Lyman limit. The estimated abundance is $2.3 \pm 0.3 \times 10^{-5}$, nearly an order of magnitude less than the high values discussed above.

Unfortunately the total column in this case is high so the HI absorption is optically thick even past the Lyman limit and the column density must be estimated from saturated features. This has led to a debate in the literature on the allowed range for the HI column and for D/H (e.g. Songaila

et al. 1997, Burles and Tytler 1997, Songaila 1997), which is likely to end up somewhere in the middle: although the total error in the abundance is probably larger than originally quoted by Tytler *et al.* (1996), the HI column is probably well enough constrained to exclude very high values like those in Q0014+813.

Therefore the dispersion in abundance between the best high and low estimates appears on the surface to be real. What is going on? There have been many suggestions (e.g., Jedamzik and Fuller 1996). Perhaps the primordial abundance is not uniform; perhaps the low-D systems have experienced stellar destruction of their deuterium; perhaps the high-D systems have found some exotic source of nonprimordial deuterium. The most prosaic explanation however is that the high-D features are all dominated by contaminating hydrogen.

2.3. Statistical Approaches to the Contamination Problem

The latter possibility deserves serious attention since the effect is known to be there and known to bias abundance estimates upwards. However, a quantitative estimate of the effect shows that it is unlikely to be important most of the time. The mean number of hydrogen lines in a velocity interval δv per $\ln(N[HI])$ interval can be estimated from the line counts of Kim *et al.* (1997) to be about

$$\delta P(N[HI]) \approx 5 \times 10^{-3} \left(\frac{\delta v}{10\mathrm{km\ sec}^{-1}}\right)\left(\frac{N[HI]}{10^{13}\mathrm{cm}^{-2}}\right)^{-0.4}.$$

If the contaminating hydrogen lines are distributed at random, we can use Poisson statistics to estimate the probability of contamination. For example, in the case of Q0014+813 the column density of the DI feature is about $10^{13.2}\mathrm{cm}^{-2}$; the probability of an HI line close to this column density appearing in the right redshift range to mimic deuterium (within an interval of about $\delta v \approx 20\mathrm{km\ sec}^{-1}$) is only about $P \approx 1\%$.

Of course, smaller amounts of contamination are more likely. They tend to bias the deuterium abundance estimates upwards and create a nongaussian (power-law) error distribution allowing low D/H with nonnegligible probability. However the magnitude of the bias is still small in this range of column density; for example, the chance of a $\approx 10\%$ contamination (for which there is indeed some evidence in Q0014+813 in the line profiles) is greater than the probability of 100% contamination by a factor of about $10^{0.4}$; but this is still only a few percent.

Furthermore this calculation does not yet allow for the additional coincidence required in the Doppler parameters. Real deuterium cannot be wider than its corresponding hydrogen. Contaminating hydrogen has a linewidth drawn at random from the parent population, which is not compatible with

a deuterium identification if it happens to exceed the width of the corresponding hydrogen feature. In the case of Q0014+813, since the D feature linewidth of 24 km $\sec^{-1}$ is typical of HI Lyman-α forest lines we should multiply the probabilities by about half to account for this effect. This factor is smaller in situations where the features are unusually narrow.

It is important to verify that the lines are uncorrelated as we have assumed. Although there are disagreements over the amplitude of line correlations the best data on the Lyman-α forest shows correlations smaller than unity at velocity separations of $\simeq 100$km $\sec^{-1}$; for example in the line lists of Kim *et al.* (1997) the amplitude is less than 10% for all lines. We have checked this also specifically for correlations with high HI column density features similar to those studied in the D candidates; although the sample is smaller and the result noisier, the amplitude of the correlation is still less than a few tenths. In this study we used one-sided correlations (counting line companions only to the red side of each Lyman-α line) in order to exclude first-order effects of deuterium contamination in the hydrogen sample. (Similar conclusions were recently reached by Songaila 1997).

Thus even without a thorough physical understanding of the absorbing material, these empirical studies indicate that correlations among the lines are too weak to alter significantly the simple estimates made on the basis of Poisson statistics. Therefore the best guess is that the deuterium abundance in cases where it appears to be high really is high, at least where the DI column is greater than about $10^{13}\mathrm{cm}^{-2}$ (which is in any case required for a reasonably precise column estimate at realistic signal-to-noise). Noting that the full error in the fitting technique has not yet been calibrated on realistic physical models of the clouds, it still seems reasonable to guess that the current data are consistent with a universal primordial abundance with a factor of two of 10^{-4}. A much more convincing measurement will be possible with a few more good targets.

2.4. Next Steps

The contamination problem is less for lower redshift, where the Lyman-α forest thins out. Although low redshift quasar spectroscopy at high resolution is costly as it requires a large investment of time with the Hubble Space Telescope, the new STIS two-dimensional spectrograph can observe the entire Lyman series at the same time; the greater efficiency will give more solid results on cases such as Q1718+4807 which are already known to be interesting (e.g. Webb *et al.* 1997) .

Contamination can also be reduced by studying high column density systems. Especially interesting are damped HI absorbers where reliable columns can be obtained for both HI and DI (Jenkins 1996), although targets are also rarer and tend to be in evolved galaxies. The best target of this type

so far identified is Q2206-199, which has a low metal abundance and a very low velocity dispersion (Pettini and Hunstead 1990).

In the long term this problem will be solved by a larger sample of absorbers in bright quasars observed from the ground. Although the current number of suitable target quasars is now quite small, the target sample in coming years will grow by about two orders of magnitude as a result of the Sloan Digital Sky Survey, so progress in this field will be limited by observing time rather than by the availability of targets.

3. The Cosmic Helium Abundance

3.1. A Bayesian Approach to Helium Enrichment

Helium abundances in extragalactic HII regions have for many years been the principal observational constraint on Big Bang Nucleosynthesis. Flourescent nebular emission lines of hydrogen and helium reveal quite precisely the number of electrons recombining into each species and thereby the abundances of each (e.g. Peimbert and Torres-Peimbert 1976, Pagel et al. 1992, Skillman and Kennicutt 1993). The techniques and estimates of systematic errors are discussed by Høg et al. (1998), Skillman et al. (1998), and Steigman et al.(1998). Here I make one simple point: the dominant source of systematic error in the primordial abundance Y_P, especially in the upper limit, probably lies not in the model used to extrapolate to zero metallicity but in the physical models used to estimate the present-day abundances Y from observations of nebulae.

Even though the bulk of the helium of the Universe originates in the Big Bang, the additional helium enrichment by stars cannot be ignored in estimating the primordial abundance from observations of present-day helium. The most widely used approach to estimate the nonprimordial enrichment is to correlate Y with metallicity Z. However, one of the limitations of this method is the need to assume a linear relation between Y and Z, which is not well motivated. Moreover most of the information on the primordial abundance is contained in the lowest metallicity points, where the correlation is not very reliably established; this information is not being efficiently used in regression fits dominated by highly enriched regions. Another approach has been to simply take the lowest, best measured points and use them as estimates of (or at least limits on) the primordial abundance. Clearly however some correction has to be made for the obvious Malmquist-like bias introduced, and some statistical way needs to be found to combine more than one region.

Hogan, Olive and Scully (1997) introduced a new statistical method to estimate the primordial helium abundance Y_p directly from helium observa-

Figure 1. Likelihood function showing 1σ, 2σ and 3σ contours in the (Y_p, w) plane, from Hogan, Olive and Scully (1997). The +'s indicate the peaks of the likelihood functions. The two left panels show results using a top-hat prior and two different subsamples of 11 and 32 lowest metal points. The two right panels show the results for positive and negative bias priors, for the 32 point sample. In all cases the conservative 2σ limit occurs at $w = 0$ and yields a limit $Y_P \leq 0.243$.

tions, without using metal abundances. They constructed a likelihood function using a Bayesian prior, encapsulating the key assumption that the true helium abundance must always exceed the primordial value, by an amount which may be as large some maximum enrichment w. They computed the likelihood as a function of the two parameters Y_p and w using samples of measurements compiled from the literature.

Some results from published samples are shown in figure 1. Estimates of Y_p vary between 0.221 and 0.236, depending on the specific subsample and prior adopted, consistent with previous estimates using different techniques. Evidence for stellar enrichment ($w \neq 0$) appears even in the lowest metallicity subsamples, but in all samples the most conservative upper bound on Y_p occurs for $w = 0$, yielding a nearly model-independent bound $Y_p < 0.243$ at 95% confidence. The main uncertainty in the Y_p bound is not the model of stellar enrichment but possible common systematic biases in the estimate of Y in each individual HII region.

3.2. Helium at High Redshift

In highly ionized environments singly ionized helium (HeII) is typically orders of magnitude more common than HI, making it the most cosmically abundant absorber, detectable even in the most rarefied regions between the Lyman-α forest clouds. Lyman-α absorption by HeII nearly continuously fills redshift space at optical depth of the order of unity as recently verified in at least three quasars (Jakobsen *et al.* 1994, Davidsen *et al.* 1996, Hogan *et al.* 1997, Reimers *et al.* 1997).

The need to model ionization states precludes a truly precise measurement of helium abundance. An absolute helium abundance can be estimated from HI and HeII Lyman-α absorption if: (1) the helium abundance is uniform; (2) HeII and HI are in ionization equilibrium dominated by photoionization; (3) we know the shape of the ionizing spectrum; (4) absorption is unsaturated, so column densities of absorbing species can measured. The total redshift integrated columns of HeII and HI are then both proportional to the same line integral $\int d\ell n_e^2$ with coefficients depending on the abundance and the ionizing spectrum.

These conditions are certainly never met in detail, but in some situations data can still be used to set constraints on the abundance and its variations. In some regions, the HeII fraction may be close to unity (Reimers *et al.* 1997); in others, the strength and/or spectrum of the ionizing field may be known, for example for gas close to the quasar (Hogan *et al.* 1997); and in some circumstances the spectrum may be approximately constant over a large pathlength along the line of sight, allowing the universality of the abundance to be constrained even if its absolute value is uncertain.

The new results are however most important not as abundance determinations but as probes of structure formation and ionization history. If we assume that the helium abundance is close to the Big Bang prediction, helium observations put stringent constraints on the density of diffuse gas at high redshift which limit the range of possible baryonic histories. For example, it is not possible to place the bulk of the baryons in a diffuse medium at $z = 3$ without exceeding helium absorption limits unless the gas is hot enough to be thermally ionized; on the other hand a substantial fraction of the baryons appear to be necessary in gaseous form (in clouds) to account for the Lyman-α forest (Rauch *et al.* 1997, Weinberg *et al.* 1997, Zhang *et al.* 1997).

4. The Cosmic Baryon Abundance and the Concordance of Standard Big Bang Nucleosynthesis

In a recent survey, Fukugita, Hogan and Peebles (1997) estimate the mean density of the Universe observed in various components of baryons, summarized in Table 1. Not included in the table are two "uncounted" components, MACHOs and hot plasma ($T \approx 2 \times 10^6$K), which are known to exist locally. For both of these almost no meaningful upper or lower bounds can be set on the global density. In the case of MACHOs, a new population of dark compact objects, probably baryonic, has been detected by microlensing in the direction of the LMC; depending on assumptions used to extrapolate, the global density of this population could either be negligible or could dominate all other forms of baryons combined. Similarly, a thermal background

from hot gas is detected, but could either be from a globally insignificant portion of the Galactic corona or from a globally distributed plasma containing the bulk of the baryons. These two components are therefore possible repositories of additional baryons.

The point here of course is to compare the observed number of baryons with the number expected on the basis of light element abundances. For the nucleosynthesis entries we adopt upper and lower limits for the primordial deuterium $2 \times 10^{-5} \leq (D/H)_P \leq 2 \times 10^{-4}$. For primordial helium we adopt a central value of $Y_P = 0.23$ and a 2σ limit as described above, $Y_P \leq 0.243$. Note that this limit is not compatible with the low deuterium values. The lithium abundance allowing for some depletion is taken to be $Li/H \leq 4 \times 10^{-10}$ from Galactic stars (see Cayrel 1998); even though it does not offer a principal constraint on baryon density in the Standard Model, it is important as a constraint on departures from the Standard Model, such as small scale inhomogeneities (e.g. Kurki-Suonio *et al.* 1997).

It is clearly instructive to contemplate these numbers at length. Most of the baryons today are still in the form of ionized gas, which contribute a mean density uncertain by a factor of about four (due to uncertainties in extrapolating from observed x-ray emission). For the best-guess plasma density, stars are a relatively minor component— all stars and their remnants comprise only about 17% of the baryons, while populations contributing most of the blue light comprise less than 5%. The formation of galaxies and of stars within them appears to be a globally inefficient process— an effect not fully understood in models of galaxy formation. The sum over the budget, expressed as a fraction of the critical Einstein-de Sitter density, is in the range $0.01 \leq \Omega_B \leq 0.04$, with a best guess $\Omega_B \sim 0.02$ (at Hubble parameter 70 km s^{-1} Mpc^{-1}). This is close to the prediction from the Standard Big Bang for moderately high $D/H \approx 10^{-4}$. If the deuterium abundance is high, this suggests we may be close to a complete survey of the major states of the baryons as well as a concordance with nucleosynthesis. On the other hand if D is low (and Y_P has been underestimated) the baryon budget is likely to be dominated by currently uncounted components. Although galaxy formation models prefer the higher baryon density (e.g. Rauch *et al.* 1997, Zhang *et al.* 1997) they do not yet predict which of the hidden forms dominates today (see e.g. Fields and Schramm 1998)— very diffuse gas or very compact cold bodies.

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Table I
The Baryon Budget (Fukugita *et al.* 1997)

	Component	Optimum	Maximum	Minimum	Grade
	observed at $z \approx 0$:				
1	stars in spheroids	0.0026 $h_{0.7}^{-1}$	0.0043 $h_{0.7}^{-1}$	0.0016 $h_{0.7}^{-1}$	A
2	stars in disks	0.00086 $h_{0.7}^{-1}$	0.00129 $h_{0.7}^{-1}$	0.00051 $h_{0.7}^{-1}$	A–
3	stars in irregulars	0.000069 $h_{0.7}^{-1}$	0.000116 $h_{0.7}^{-1}$	0.000033 $h_{0.7}^{-1}$	B
4	neutral atomic gas	0.00033 $h_{0.7}^{-1}$	0.00041 $h_{0.7}^{-1}$	0.00025 $h_{0.7}^{-1}$	A
5	molecular gas	0.00022 $h_{0.7}^{-1}$	0.00029 $h_{0.7}^{-1}$	0.00014 $h_{0.7}^{-1}$	A–
6	plasma in clusters	0.0026 $h_{0.7}^{-1.5}$	0.0044 $h_{0.7}^{-1.5}$	0.0014 $h_{0.7}^{-1.5}$	A
7	plasma in groups	0.014 $h_{0.7}^{-1}$	0.03 $h_{0.7}^{-1}$	0.007 $h_{0.7}^{-1}$	B
	sum (at $h = 0.7$)	0.02	0.04	0.01	
	observed at $z \approx 3$:				
10	damped absorbers	0.001– 0.002 $h_{0.7}^{-1}$	0.0027 $h_{0.7}^{-1}$	0.007 $h_{0.7}^{-1}$	A–
11	Lyman-α forest clouds	0.038 $h_{0.7}^{-2}$		0.025 $h_{0.7}^{-2}$	B
12	intercloud gas (HeII)		0.01 $h_{0.7}^{-1.5}$	0.0001 $h_{0.7}^{-1}$	B
	nucleosynthesis:				
9a	deuterium		0.054 $h_{0.7}^{-2}$	0.013 $h_{0.7}^{-2}$	A
9b	helium	0.010 $h_{0.7}^{-2}$	0.027 $h_{0.7}^{-2}$		A–
9c	lithium		0.06 $h_{0.7}^{-2}$	0.007 $h_{0.7}^{-2}$	B

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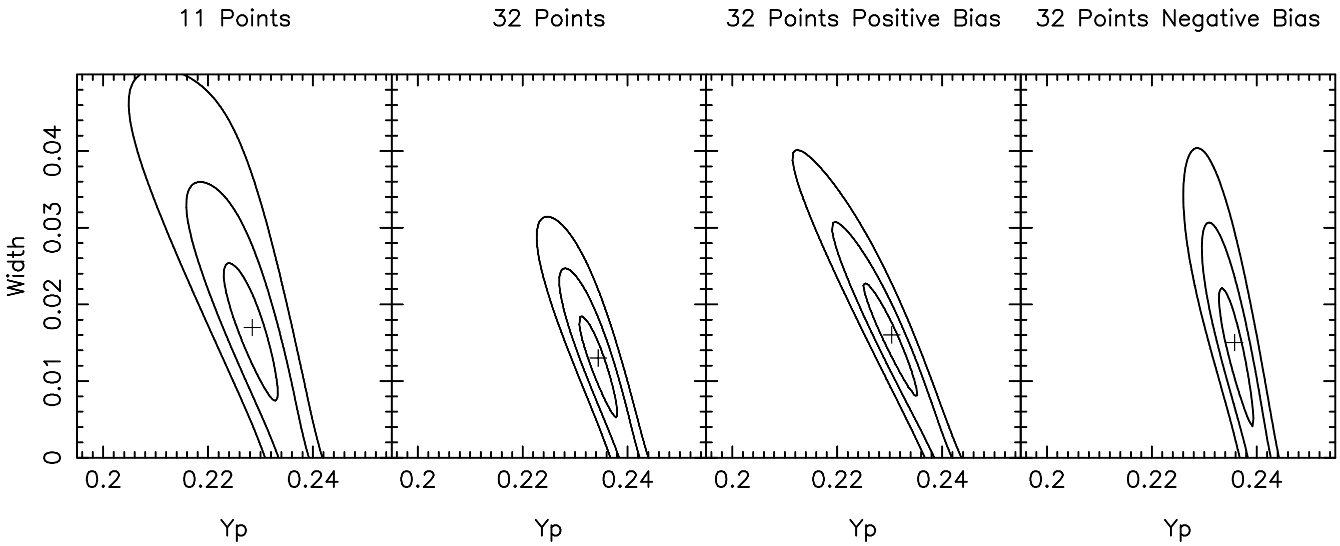
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